https://doi.org/10.1038/s41550-024-02430-5

The X-ray mysteries of neutron stars and white dwarfs

Check for updates

These two types of compact objects share several similarities, despite their different compositions. A short workshop in Spain brought communities together to share understanding of dense matter under extreme conditions.

The X-ray emission from neutron stars and white dwarfs has been the subject of extensive research since the first astronomical X-ray instruments. The first X-ray source ever discovered, Sco X-1 in 1962 (even before the discovery of pulsars by Jocelyn Bell in 1967), is indeed an accreting neutron star with a low-mass stellar companion. The European Space Agency (ESA) mission XMM-Newton is the largest and most sensitive X-ray instrument to date, and in its 25 years of scrutinizing the high-energy sky, has observed hundreds of neutron stars and white dwarfs, unveiling unique insights into the energetic phenomena occurring within these compact stellar remnants. A meeting in June 2024 gathered experts from various disciplines at the ESA centre near Madrid to delve into the latest advancements in understanding the emission processes and origin of X-rays, synergies with other multi-band and multi-messenger facilities, and the astrophysical implications associated with neutron stars and white dwarfs (Fig. 1).

Starting with the pulsar population, now comprising around 3,000 objects known in the Milky Way, Aris Karastergiou showed the results of the 'The Thousand Pulsar Array program', a pioneering initiative active since 2019, which harnesses the capabilities of the MeerKAT radio telescope. This programme represents a crucial step towards unravelling the enigmatic realm of pulsar birth rates, evolutionary trajectories, and the intricate nuances of their radiation profiles, spectra, and polarization properties. The large sample of pulsars observed with exquisite detail promises to reveal their relations with magnetar-like

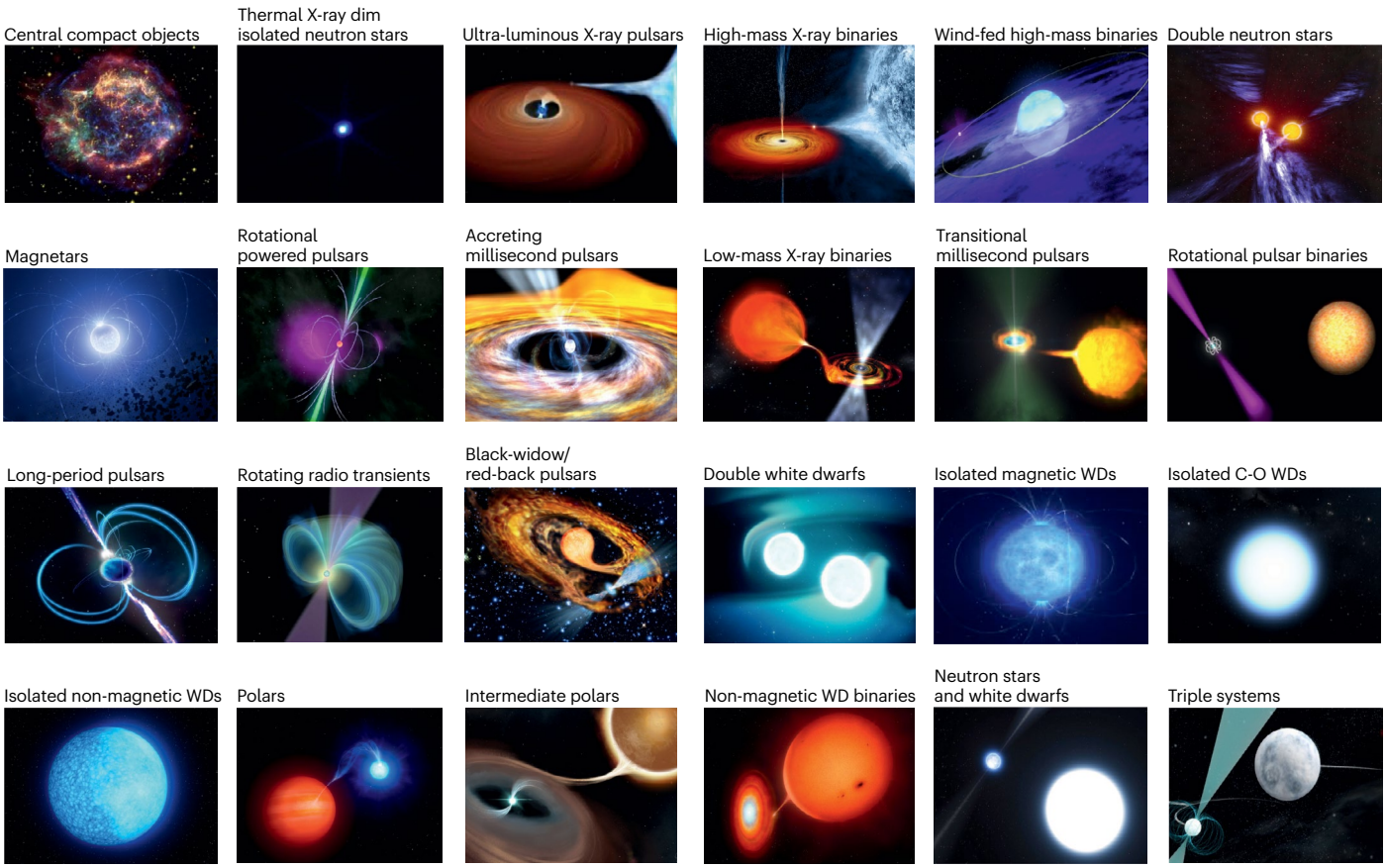

Fig. 1 | Collection of the different types of neutron star and white dwarf systems known to date and observed in our Galaxy. The first two images from the top left are produced using X-ray data from Chandra and XMM-Newton (respectively). Other images are artistic impressions used to explain the nature and geometry of the different systems.

CREDIT: SCIENCE PHOTO LIBRARY / ALAMY STOCK PHOTO ('POLARS', 'NON-MAGNETIC WD BINARY')

neutron stars, long period transients (LPTs), and the elusive domain of fast radio bursts (FRBs).

LPTs were presented by Natasha Hurley-Walker. Recent radio astronomical observations have unveiled the emergence of these new Galactic radio sources characterized by their exceedingly prolonged periods spanning tens to hundreds of minutes. These sources emanate bright, highly polarized emissions reminiscent of pulsars and magnetars yet they exhibit atypical sluggish periodicity. Delving into the exploration of these enigmatic entities raises compelling questions surrounding their classification as potential ultra-long period magnetars, or radio-bright white dwarf systems, or the emergence of an entirely novel astronomical phenomenon.

The Milky Way is expected to house approximately a billion neutron stars, but yet paradoxically, only a few thousand have been discovered. Vanessa Graber underscored the observational constraints limiting our scrutiny to a mere fraction of these compact stars. In a bid to bridge this observational chasm, she presented a new simulation framework motivated by the advent of a groundbreaking simulation-based inference approach anchored on neural networks.

Strategic deliberations extended beyond the realms of pulsar dynamics to embrace the staggering phenomenon of FRBs, intense radio signals originating from enigmatic extragalactic sources. With no detectable electromagnetic radiation outside the radio band, FRBs present an astrophysical mystery. A tantalizing connection linking FRBs to magnetars via the detection of an X-ray burst emanating from the Galactic magnetar SGR 1935+2154 is poised to reshape our understanding of these transient cosmic beacons. Aaron Pearlman presented an extensive search and analysis through the latest X-ray observations surrounding FRBs and charted the future trajectory towards the detection of X-ray emissions from nearby FRBs.

Alice Borghese presented the discovery of new magnetars via their X-ray outbursts. Magnetars, neutron stars adorned with prodigious magnetic fields, cast an ethereal spectacle of X-ray and gamma-ray bursts, epitomize the capricious yet captivating nature of cosmic phenomena, shedding light on the interaction of matter and strong magnetic fields, like a plasma laboratory for regimes unreachable on Earth. Recent advancements in numerical modelling have significantly improved our physical interpretation of these processes, with models now aligning well with observations. Sam Lander and Davide De Grandis presented the current understanding of magnetic field evolution in neutron stars and the modelling of these magnetar outbursts.

Neutron star temperatures herald insights into the profound interiors of these dense stars, unravelling their enigmatic core compositions, superfluid dynamics, and cooling mechanisms. Craig Heinke illuminated the theoretical underpinnings of observational constraints and the intricacies of crustal cooling mechanisms. Observational results anchoring on temperature measurements of young neutron stars like Cas A and accreting neutron stars post-outburst, are pivotal results to unfold the properties of the dense core-matter of neutron stars. Following on, Alessio Marino showed temperatures of what are to date the coldest isolated neutron stars ever discovered, measured by XMM-Newton and Chandra.

However, over 50 years after their discovery, the internal composition and structure of neutron stars remain a mystery due to the extreme densities that cannot be replicated in Earth laboratories. Determining the equation of state of nuclear matter within neutron stars would significantly impact both astrophysics and nuclear physics. Neutron-star mass measurements, available since the 1970s from binary radio pulsars, provide precise data, while radius measurements, particularly from X-ray observatories like NICER, have recently become more accurate. Sebastien Guillot presented recent radius measurements with NICER and XMM-Newton and discussed future observational prospects with NewAthena.

Neutron stars in binary systems were presented in several talks, over the range of their evolutionary diversity: transitional millisecond pulsars, low-mass X-ray binaries, high-mass X-ray binaries and ultra-luminous X-ray pulsars. Maria Cristina Baglio covered a recent discovery about transitional millisecond pulsars, which can switch between X-ray and radio states within days due to changes in mass-accretion rates.

The discovery of several ultra-luminous X-ray sources (ULXs) with fast, rapidly evolving X-ray pulsations has confirmed their association with accreting neutron stars orbiting massive companion stars. Notably NGC5907 ULX-1, the brightest pulsating ULX, exhibits a luminosity exceeding its Eddington limit by up to 1,000 times. GianLuca Israel provided an overview of the ULX class, focusing on recent findings from four new pulsating ULXs.

White dwarfs and neutron stars share a variety of physics, from accretion phenomena and dense plasma physics, to cooling mechanisms. White dwarfs, the most common end-state of stars, also offer insights into late stellar evolution, and our Galaxy's structure. Ilaria Caiazzo presented the discovery of the most magnetic isolated white dwarfs, with field strengths reaching a billion Gauss. The reasons why only certain white dwarfs are magnetic remain unresolved.

From a population point of view, Maria Camisassa reported on the results from the Gaia mission, which has significantly advanced this field by providing detailed data on nearly 360,000 white dwarfs, including their chemical abundances and magnetic fields. This extensive dataset has generated new questions about the nature of white dwarfs, requiring deeper theoretical modelling and statistical analysis.

Accreting white dwarfs often show X-ray and radio emission, but non-accreting white dwarfs rarely do so. Ingrid Pelisoli showed the groundbreaking discovery of radio emission from two non-accreting white dwarf binaries, the different models explaining their emissions, and the theory possibly explaining the formation of these binary systems.

On the other hand, cataclysmic variables (CVs) are binary systems where a white dwarf accretes matter from a main sequence companion, similar to low-mass X-ray binaries in the neutron star case. Aarran Shaw and Simone Scaringi highlighted recent findings on magnetic CVs, focusing on the mass distribution of their white dwarfs, the discovery of their tendency to transition to unusual low-flux states, as well as the presence of micronovae. Furthermore, similarly to neutron star accreting systems, they present thermonuclear explosions on different scales and ranges. Erik Kuulkers showed detections of neutron star type I bursts dating back to the first X-ray data in the 1970s. New 2D/3D models presented by Jordi José showed with exquisite detail the mixing at the core–envelope interface and interactions between nova ejecta, the accretion disk, and the secondary star.

White dwarfs and neutron stars are the most compact and extreme stars in the Milky Way, and beyond, among the strongest and most variable X-ray emitters in the Galaxy; they offer unique insights into extreme matter and gravity, stellar evolution and its final stages, and the fundamental nature of spacetime.

Meeting report

Nanda Rea [1,2] ✉ **& Norbert Schartel** [3]
[1]Institute of Space Sciences (ICE), CSIC, Campus UAB, Barcelona, Spain. [2]Institut d'Estudis Espacials de Catalunya (IEEC), Mediterranean Technology Park (PMT), Castelldefels, Spain. [3]European Space Agency, Villanueva de la Cañada, Madrid, Spain.
✉e-mail: rea@ice.csic.es

Published online: 28 November 2024

Competing interests
The authors declare no competing interests.